Traffic & Transportation

Methodology of Choosing the Most Eco-Friendly Waste Collection Truck

Ondrej STOPKA[1], Vladimír ĽUPTÁK[2], Mária STOPKOVÁ[3], Branislav ŠARKAN[4], Jaroslav MAŠEK[5]

Original Scientific Paper
Submitted: 5 Nov 2024
Accepted: 17 Dec 2024

[1] Corresponding author, stopka@mail.vstecb.cz, Department of Transport and Logistics, Faculty of Technology, Institute of Technology and Business in České Budějovice, České Budějovice, Czech Republic
[2] luptak@mail.vstecb.cz, Department of Transport and Logistics, Faculty of Technology, Institute of Technology and Business in České Budějovice, České Budějovice, Czech Republic
[3] stopkova@mail.vstecb.cz, Department of Transport and Logistics, Faculty of Technology, Institute of Technology and Business in České Budějovice, České Budějovice, Czech Republic
[4] branislav.sarkan@uniza.sk, Department of Road and Urban Transport, University of Žilina, Žilina, Slovakia
[5] jaroslav.masek@uniza.sk, Department of Railway Transport, University of Žilina, Žilina, Slovakia

Publisher:
Faculty of Transport and Traffic Sciences, University of Zagreb

ABSTRACT

The waste collection in the territory of urban agglomerations, as a part of city logistics approaches, has become one of the key topics due to growing demands for logistic operations in cities burdened by high traffic volumes, worsening the quality of life and the environment in cities. Congested traffic ails České Budějovice, especially during peak hours. Congestions should partially be avoided by the planned construction of new roads to divert transit traffic from the city centre. Despite these remedial measures, the current transport and logistic situation requires further improvement. The paper focuses on waste collection, which significantly affects the traffic flow in České Budějovice. Currently, the city uses costly CNG-propelled trucks, which release a lot of harmful emissions. The paper aims to consider and evaluate new approaches to waste collection that could work in compliance with ecological principles and sustainable urban development of cities. This matter embraces waste collection trucks propelled by hydrogen, electricity, biogas and CNG. In other words, the decision needs to be made on whether it makes sense to invest in up-to-date and sustainable technologies to fuel waste collection trucks in a territory under investigation. To this end, multicriteria decision-making methods are applied, namely, Saaty and Fuller methods – to quantify the criteria weights, and the PROMETHEE and the ORESTE methods – to identify a compromise (ideal) variant. The findings encompass the decision-making process and a draft methodology concerning the determination of rank of the considered waste collection trucks based on relevant criteria set identified by the expert evaluation.

KEYWORDS

city logistics; waste collection; multicriteria decision making; alternative sources of energy.

1. INTRODUCTION

Growing demands for the quality of logistic operations within urban areas have recently made city logistics a widely discussed issue. Citizens complain about high traffic volumes polluting the environment near their homes, strikingly contrasting with an increasing traffic demand. Cities, and above all their inhabitants, are today experiencing a series of issues associated with high traffic volumes. As for city residents, the state of the environment around their homes is a crucial topic. This has been increasingly threatened by rising transport-related demands. This stalemate calls for optimising traffic flows and logistic operations within and outside urban areas, tapping into well-established city logistics concepts to improve the situation. City logistics has been an increasingly mentioned concept as the demands for logistic operations in city areas have expanded.

To this end, it is necessary to continually take into consideration the optimisation of logistic flows and operations both outside and inside cities, ideally utilising already known city logistic approaches and measures that can lead towards enhancement in the overall traffic situation. With an ongoing expansion of alternative energy sources, new opportunities arise to improve living conditions for residents in busy parts of cities.

The city of České Budějovice serves as a sample for exploring new possibilities of city logistics to optimise and enhance traffic flows without harming the environment and life of the local citizens. České Budějovice has long been known for its constant traffic hold-ups and congestion during rush hours. A planned development of new road networks should divert heavy goods vehicle traffic outside the city centre and adjacent areas. Regardless of the success of these plans, the situation in České Budějovice will be far from perfect – including the area of waste collection.

The subject of the paper is to conduct research aimed at new options for city logistic approaches in the city of České Budějovice, which would assist towards minimising and enhancing traffic and its impacts on the environment and the quality of life for residents in this area. České Budějovice was chosen because the city's residents and traffic participants suffer, especially during rush hours, from high traffic intensity on the road network. In order to optimally design new scenarios, multicriteria decision-making methods are used in the manuscript. These include Saaty pairwise comparison and Fuller methods to quantify the criteria weights, as well as the PROMETHEE and ORESTE methods for determining the optimal (compromise) variant of solution.

2. LITERATURE REVIEW

The paper focuses on city logistics with an emphasis on ecology (green) transport, reduction of emissions by using alternative (nonconventional) types of vehicles, and improving the environment quality. For this reason, a literature review was conducted dealing with publications related to these topics. The first publications examined pertained to the concept of city logistics and green transport aimed at mitigating emissions and utilising vehicles with alternative propulsion systems (or fuels).

The publications [1–3] inform on urban logistics, focusing on effective road haulage in urban areas while avoiding the disruption of traffic flows [1], ensuring safety [2] and eco-friendliness [3]. The authors define city logistics as city freight distribution, last-mile delivery and urban sprawl freight distribution. Many studies have delved into a tapestry of concepts, measures and technologies of city logistics, while the publications [4–6] analyse the city logistic planning [4], short-term logistic processes integrated planning and resource management [5] involving a two-layer distribution structure [6].

When deciding upon implementing city logistics, we examined the relevant literature sources, focusing on articles dealing with logistic solutions in specific towns. These include scholarly publications on sustainable and green passenger transport and haulage [7], encompassing material, goods, and citizen flows inside the city and urban sprawls. Other studies [8] cover a methodology for measuring direct and indirect emissions and internalising external costs of road transport services, including various types of vehicles, exploring the perks of using alternative fuel vehicles for waste collection in the city.

The works [9, 10] explore logistic initiatives for cutting emissions from road haulage and air pollution. The authors of the articles [11, 12] conducted a case study on the use of alternatively fuelled vehicles in urban sprawls in Beijing, achieving a CO_2 reduction when collecting and delivering shipments. The publication [13] by Sierpinsky et al. suggests that transport is critical for city logistics, requesting a redistribution of the transport and transition to new energy sources, including electromobility. Technological development has made electric vehicles more eco-friendly, significantly reducing harmful emissions.

In the study [14], van Duin and col., analyse the feasibility and effectiveness of city distribution terminals based on their experience from The Hague and other cities. Lindholm and Behrends [15] examine how transport systems adapt to long-term restrictions. The research [16] assesses the efficiency of freight deliveries outside the rush hour, revealing that moving road haulage deliveries outside the peak hour may speed up the delivery process and mitigate the negative impact on the environment. Its results are valuable for the government and industrial experts [17].

The second part of the literature review is aimed at the field of multicriteria analysis and its use in the context of city logistics and its planning with an emphasis on reducing harmful substances. The literature [18] devised a method of multicriteria decision-making support when planning supply points, focusing on cutting noxious substances like carbon dioxide, nitrogen oxides and solid particles [19]. The authors identified the criteria of complex decision-making and the process of determining alternatives using the Saaty pairwise comparison method (Analytic Hierarchy Process).

The city of České Budějovice and other cities already use CNG-propelled waste collection trucks. Based on fossil fuels, the production of compressed natural gas is costly and environmentally dangerous, with bleak long-term prospects. Some automotive producers have been phasing out the production of CNG-fuelled vehicles, focusing more on electromobiles and hydrogen [20, 21]. Although trucks are exempt from this alteration, we must think about more sustainable and eco-friendly solutions.

However, in this manuscript, new solutions concerning city logistics approaches are proposed when using multicriteria decision-making methods, including the Saaty and Fuller methods for breaking down the criteria into a hierarchical structure, as well as the PROMETHEE and the ORESTE for determining the best alternative.

3. DATA AND METHODS

We analyse waste collection vehicles used throughout European countries to explore new alternatives. These eco-friendly trucks run on hydrogen, electricity, biogas and CNG to assess whether an investment in modern technologies will be profitable. The vehicles are as follows:

— v_1 Mercedes Benz GEN2H Hydrogen;
— v_2 Volvo FE Electric Electricity;
— v_3 Dennis Eagle EV Electricity;
— v_4 Lion 8 EL Electricity;
— v_5 Renault Trucks D Wide CNG;
— v_6 IVECO Strails CNG;
— v_7 Scania P 340 Biogas.

We discussed and assessed the analysed criteria with many experts from the automotive industry, academic field, locals and representatives of adjacent municipalities, gathering the information during August and September 2023. Each criterion was identified as relevant based on the practical experience and knowledge of the expert team assessment, which included various specialists. The entire process of criterion set development combined practical experience with academic research, providing a reliable foundation for specifying the most suitable waste collection vehicle. These criteria represent an intersection of various stakeholders, making the outcomes not only expert-driven, thereby adequate, but applicable as well. The data processing was done by the following specialists:

— team leader of the research and development of non-traditional fuels;
— marketing specialist on non-traditional fuels;
— project manager supervising the application of traditional fuels;
— project manager supervising the application of non-traditional fuels;
— development engineer dealing with traditional fuels;
— development engineer dealing with non-traditional fuels;
— 2 x citizen of the city of České Budějovice;
— 2 x transport officer of the city of České Budějovice.

The criteria for a suitable vehicle were as follows:

— k_1 Refuelling time [min];
— k_2 Number of gas stations in the city (České Budějovice) [-];
— k_3 Maximum mileage [km];
— k_4 Solid waste capacity [m^3];
— k_5 Average operating cost of the vehicle in operation in the Czech Republic [CZK/km];
— k_6 CO_2 reduction considering fuel production compared to traditional engines [%];
— k_7 Share of fossil fuels during production [%];
— k_8 Fuel potential over the next ten years [-];
— k_9 Purchasing cost (acquisition price) of the vehicle [million CZK].

We use multicriteria analysis for evaluating the best alternative. *Table 1* suggests the acquired input data, including the nature of the criteria in the last line. Criterion 8, i.e. fuel potential within the next ten years came as a mean value calculated from an evaluation made by six automotive industry experts, resulting in a professionally certified rating scale. The data were gathered during September 2023 from the following specialists:

— team leader of the research and development of non-traditional fuels;
— marketing specialist on non-traditional fuels;
— project manager supervising the application of traditional fuels;
— project manager supervising the application of non-traditional fuels;
— development engineer dealing with traditional fuels;
— development engineer dealing with non-traditional fuels.

The rating scale correlates with the data from k_8:

— zero potential 0;
— low potential 1;
— medium potential 2;
— high potential 3;
— enormous potential 4.

We chose two methods for processing and comparing the results of the multicriteria analysis, including the Saaty method for determining the weight of the criteria and the PROMETHEE for selecting the best alternative [22, 23]. We applied the Fuller method to define the weight of criteria and the ORESTE technique to compare the options [24]. When conducting the multicriteria analysis, we omit all repeating calculations but give an example of the specific step.

Table 1 – Multicriteria analysis input data

	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9
v_1	10	0	160	23	2.5	30	96	3	15
v_2	120	25	100	23	1.5	50	39	4	9
v_3	180	25	150	10	1.5	50	39	4	6
v_4	240	25	200	15.3	1.5	50	39	4	8
v_5	10	5	800	22	2.9	30	100	2	6
v_6	10	5	600	12	2.9	30	100	2	4
v_7	10	2	350	22	2.9	90	0	3	5
Nature	MIN	MAX	MAX	MAX	MIN	MAX	MIN	MAX	MIN

Source: the Authors

For the selected methods of multicriteria analysis, we had to "normalise" *Table 1* and convert minimising criteria k_1,k_5,k_7 a k_9 to maximising.

Table 2 – Normalised table for the PROMETHEE and the ORESTE

	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9
v_1	240	0	160	23	1.9	30	4	3	4
v_2	130	25	100	23	2.9	50	61	4	10
v_3	70	25	150	10	2.9	50	61	4	13
v_4	10	25	200	15.3	2.9	50	61	4	11
v_5	240	5	800	22	1.5	30	0	2	13
v_6	240	5	600	12	1.5	30	0	2	15
v_7	240	2	350	22	1.5	90	100	3	14
Nature	MAX	MAX	MAX	MAX	MAX	MAX	MAX	MAX	MAX

Source: the Authors

4. RESULTS

The objective of the research is to identify a suitable type of vehicle for waste collection when taking into account the impact on environmental quality and ensuring sustainable urban development. Since several possible scenarios to the issue were regarded and multiple criteria needed to be taken into consideration, multi-criteria analysis has been applied for this purpose.

In addressing the problem, the following steps were necessary: (1) identifying the suitable criteria, (2) quantifying the weights of the identified criteria according to their importance, (3) selecting the best possible option and (4) verifying the results.

The assessed criteria are related to the ecological, economic and technical aspects of waste collection. For quantifying the criteria weights, for expert assessment and comparison of the criteria according to their significance, the Saaty pairwise comparison method is applied. The significance of each criterion was calculated based on expert evaluations, providing an objective framework for selecting the compromise option.

To select the best option, the PROMETHEE method was used. PROMETHEE is a pairwise comparison method that allows for direct comparison of individual variants based on multiple criteria, taking into account a preference function that evaluates the differences between two options for each criterion. The outcome is represented by a global preference index that ranks the variants according to their preferences.

To verify the results, the Fuller method was used, which, similarly to the Saaty method, serves to assess criteria based on preference differences. Subsequently, the ORESTE method was applied, which allows for processing these preference differences and provides alternative results for the ranking of evaluated vehicles.

Following the abovementioned, for the sake of this study, the combination of all those methods of investigation is inevitable to be applied in order to achieve the best possible outcomes.

4.1 Determining the criteria weights (Saaty method)

We chose the Saaty and the PROMETHEE method for selecting the optimum alternative using the following rating scale for criteria (we could also use even numbers in the event of a too rough scale).

— 1 Elements are of equal importance;
— 3 Line element is slightly more important than column;
— 5 Line element is significantly more important than column;
— 7 Line element is very significantly more important than column;
— 9 Line element is extremely more important than column.

The selected experts filled out a brief form to gather the input data, evaluating the suggested criteria according to the rating scale above. *Table 3* depicts the averaged resulting values. After the values were rated, we calculated the geometric mean of each line according to *Formula 1*.

$$G(x_1, x_2, \dots, x_n) = \sqrt[n]{x_1 * x_2 * x_n} \tag{1}$$

To achieve all geometric means, we calculated the weights of the criteria according to *Formula 2*, suggesting the weight calculated for k_1.

$$v_i = \frac{G_i}{\sum_{i=1}^{n} Gi} \tag{2}$$

Table 3 illustrates the weights calculated in the same way for the remaining criteria, assigning the greatest importance to k_2 number of gas stations in the city, whilst maximum mileage, k_3, ranks the last.

Table 3 – Saaty method vector weights for the criteria

	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9	Geometric mean	Criterion weight
k_1	1	1/7	1	1/4	1/4	1/6	1/5	1/8	2	0.347767481	0.025485133
k_2	7	1	7	6	7	4	4	3	6	4.37951914	0.320940375
k_3	1	1/7	1	1/2	1/4	1/8	1/5	1/5	1/5	0.29677243	0.021748108
k_4	4	1/6	2	1	4	1/5	1/4	1/6	3	0.799412566	0.058582634
k_5	4	1/7	4	1/4	1	1/5	1/4	1/7	1/2	0.502445921	0.036820294
k_6	6	1/4	8	5	5	1	2	1/4	5	2.086657888	0.152914679
k_7	5	1/4	5	4	4	1/2	1	1/3	4	1.594617503	0.116856925
k_8	8	1/3	5	6	7	4	3	1	4	3.105695031	0.227591865
k_9	1/2	1/6	5	1/3	2	1/5	1/4	1/4	1	0.533008541	0.039059987

Source: The Authors

4.2 The PROMETHEE method for selecting the compromise vehicle

The PROMETHEE method closely follows the Saaty method, using a normalised table of alternatives and criteria with calculated weights (*Table 2* and *3*). It involves comparing all alternatives according to all input criteria, upon knowing the weights of the values. We compare two alternatives for a given criterion using preference functions rated from 0 to 1. The preference functions may be chosen according to the selected criterion and is defined as follows (*Formula 3*):

$$P(d) = \begin{cases} 0, d \leq q \\ 1, d > q \end{cases}; q=60 \tag{3}$$

Upon determining all criterion values, we calculated a preference index for each alternative according to *Formula 4* suggested in *Table 4*.

$$\Pi(a,b) = \sum_{j=1}^{k} P_j(a,b) * v_j, \Pi(a,a) = 0 \tag{4}$$

Table 4 – The PROMETHEE criterion k_1

	k_1	k_2	k_3	k_4	k_5	k_6	k_7
v_1	-	1	1	1	0	0	0
v_2	0	-	0	1	0	0	0
v_3	0	0	-	0	0	0	0
v_4	0	0	0	-	0	0	0
v_5	0	1	1	1	-	0	0
v_6	0	1	1	1	0	-	0
v_7	0	1	1	1	0	0	-

Source: the Authors

Upon determining all preference indexes, we calculated a positive and negative flow. The former (*Formula 5*) is always decided for the whole line and the latter (*Formula 6*) for the whole column of the table.

$$\emptyset^{+}(a) = \frac{1}{n-1} \sum_{x \in A} \Pi(a,x) \tag{5}$$

$$\emptyset^{-}(a) = \frac{1}{n-1} \sum_{x \in A} \Pi(x,a) \tag{6}$$

Upon calculating all positive and negative flows, we determined global preference indexes for all alternatives, achieved by *Formula 7*.

$$\emptyset(a) = \emptyset^{+}(a) - \emptyset^{-}(a) \tag{7}$$

Table 5 depicts the results of all global preference indexes.

Table 5 – The PROMETHEE – Global preference indexes

	k_1	k_2	k_3	k_4	k_5	k_6	k_7	**Positive flow**	**Global preference index**
v_1	-	0.0309	0.0841	0.0724	0.0074	0.0659	0.0074	0.0447	-0.2459
v_2	0.4576	-	00586	0.0724	0.6722	0.7308	0.3430	0.3891	0.3303
v_3	0.4576	0.0156	-	0.0078	0.6722	0.6722	0.3430	0.3614	0.2715
v_4	0.4576	0.0054	0.0351	-	0.6722	0.6956	0.3430	0.3682	0.2866
v_5	0.0608	0.0629	0.1058	0.0902	-	0.0749	0.0217	0.0694	-0.3015
v_6	0.0608	0.0785	0.0668	0.0707	0.0078	-	0.0217	0.0510	-0.3642
v_7	0.2487	0.1597	0.1894	0.1762	0.1933	0.2519	-	0.2032	0.0232
Negative flow	0.2905	0.0588	0.0900	0.0816	0.3709	0.4152	0.1800		

Source: the Authors

Global preference index values indicate the following order of the alternatives, showing the alternative with the highest preference.

— v_2 Volvo FE Electric ELECTRICITY;
— v_4 Lion 8 EL ELECTRICITY;
— v_3 Dennis Eagle EV ELECTRICITY;
— v_7 Scania P 340 BIOGAS;
— v_1 Mercedes Benz GEN2H + Strummer HYDROGEN;
— v_5 Renault Trucks D Wide CNG;
— v_6 IVECO Stralis CNG.

4.3 Determining the criteria weights (Fuller method)

Upon evaluating the PROMETHEE method, which determined the Volvo FE Electric running on electricity as the optimum alternative, we used the Fuller method to specify criteria weights followed by the ORESTE technique.

The Fuller approach involved a questionnaire and diagram made by the standards and given to experts to fill in in. The evaluators were asked to select a more important alternative of the criterion. We then chose the most preferred option and compiled a diagram containing the order of the criteria. The following line diagram (*Figure 1*) suggests the preferences, highlighting the most preferred criterion in bold.

k_1	$\boldsymbol{k_1}$	k_1	k_1	k_1	k_1	k_1	$\boldsymbol{k_1}$
$\boldsymbol{k_2}$	k_3	$\boldsymbol{k_4}$	$\boldsymbol{k_5}$	$\boldsymbol{k_6}$	$\boldsymbol{k_7}$	$\boldsymbol{k_8}$	k_9
	$\boldsymbol{k_2}$	$\boldsymbol{k_2}$	$\boldsymbol{k_2}$	$\boldsymbol{k_2}$	$\boldsymbol{k_2}$	$\boldsymbol{k_2}$	$\boldsymbol{k_2}$
	k_3	k_4	k_5	k_6	k_7	k_8	k_9
		k_3	k_3	k_3	k_3	k_3	k_3
		$\boldsymbol{k_4}$	$\boldsymbol{k_5}$	$\boldsymbol{k_6}$	$\boldsymbol{k_7}$	$\boldsymbol{k_8}$	$\boldsymbol{k_9}$
			$\boldsymbol{k_4}$	k_4	k_4	k_4	$\boldsymbol{k_4}$
			k_5	$\boldsymbol{k_6}$	$\boldsymbol{k_7}$	$\boldsymbol{k_8}$	k_9
				k_5	k_5	k_5	k_5
				$\boldsymbol{k_6}$	$\boldsymbol{k_7}$	$\boldsymbol{k_8}$	$\boldsymbol{k_9}$
					$\boldsymbol{k_6}$	k_6	$\boldsymbol{k_6}$
					k_7	$\boldsymbol{k_8}$	k_9
						k_7	$\boldsymbol{k_7}$
						$\boldsymbol{k_8}$	k_9
							$\boldsymbol{k_8}$
							k_9

Figure 1 – The preferences, highlighting the most preferred criterion in bold. Source: authors

The diagram involves a partial number of preferences for all criteria n_i ($n_1 = 2, n_2 = 8, n_3 = 0, n_4 = 4, n_5 = 2, n_6 = 6, n_7 = 5, n_8 = 7, n_9 = 2$).

The following ORESTE method required only the order of the analysed criteria, so we did not have to calculate their weights. The highest number of preferences indicates the most important criterion and vice versa.

In the event of an equal number of preferences, we consider the placing average. The order of the criteria for the ORESTE method is as follows:

— k_2 Number of gas stations in the city [-];
— k_8 Fuel potential over the next ten years [-];
— k_6 CO_2 reduction considering fuel production compared to traditional engines [%];
— k_7 Share of fossil fuels during production [%];
— k_4 Solid waste capacity [m^3];
— k_1 Refuelling time [min];
— k_5 Average operating cost of the vehicle in operation in the Czech Republic [CZK/km];
— k_9 Purchasing cost (acquisition price) of the vehicle [million CZK];
— k_3 Maximum mileage [km].

4.4 The ORESTE method for selecting the compromise vehicle

The first step involves vector q and matrix P. Vector q defines the arrangement of the criteria depicted in *Formula 8*:

$$q = (q_1, \dots, q_k) \tag{8}$$

where q_i represents the position of the jth criterion.

Where p_{ij} represents the position of the alternative a_i according to the j[th] criterion. If the values of the criteria are equal, we consider their placing average. Matrix P is as follows (*Formula 9*):

$$P = \begin{bmatrix} 2.5 & 7 & 5 & 1.5 & 4 & 6 & 5 & 4.5 & 7 \\ 5 & 2 & 7 & 1.5 & 2 & 3 & 3 & 2 & 6 \\ 6 & 2 & 6 & 7 & 2 & 3 & 3 & 2 & 3.5 \\ 7 & 2 & 4 & 5 & 2 & 3 & 3 & 2 & 5 \\ 2.5 & 4.5 & 1 & 3.5 & 6 & 6 & 6.5 & 6.5 & 3.5 \\ 2.5 & 4.5 & 2 & 6 & 6 & 6 & 6.5 & 6.5 & 1 \\ 2.5 & 6 & 3 & 3.5 & 6 & 1 & 1 & 4.5 & 2 \end{bmatrix} \tag{9}$$

The second step involves creating a matrix of the distances from the fictitious beginning marked as $D = (d_{ij})$. The constituents of this matrix are calculated by *Formula 10*.

$$d_{ij} = \left[\frac{(p_{ij})^r}{2} + \frac{(q_j)^r}{2}\right]^{1/r}, r \in R \tag{10}$$

The next created matrix D (*Formula 11*) was restricted to four decimal places is a s follows:

$$D = \begin{bmatrix} 5.639 & 5.5613 & 7.5302 & 4.0039 & 5.882 & 4.9529 & 4.5549 & 3.6733 & 7 \\ 6.1622 & 1.651 & 8.1231 & 4.0039 & 5.5988 & 3 & 3.57 & 2 & 6.5382 \\ 6.5382 & 1.651 & 7.7887 & 6.1622 & 5.5988 & 3 & 3.57 & 2 & 5.7784 \\ 7 & 1.651 & 7.3465 & 5 & 5.5988 & 3 & 3.57 & 2 & 6.1622 \\ 5.639 & 3.5847 & 7.1466 & 4.3784 & 6.5382 & 4.9529 & 5.5322 & 5.2087 & 5.7784 \\ 5.639 & 3.5847 & 7.1693 & 5.5451 & 6.5382 & 4.9529 & 5.5322 & 5.2087 & 5.5613 \\ 5.639 & 4.7695 & 7.2304 & 4.3784 & 6.5382 & 2.4101 & 3.1913 & 3.6733 & 5.5988 \end{bmatrix} \tag{11}$$

The third step includes arranging and ranking d_{ij} values from the matrix from the lowest to the highest. We then replace d_{ij} values with the final order within the newly created matrix $R = (r_{ij})$. If more d_{ij} values are the same, we consider the ranking average. The newly formed matrix R (*Formula 12*) is as follows:

$$R = \begin{bmatrix} 41.5 & 34.5 & 61 & 19.5 & 46 & 26 & 23 & 17.5 & 55.5 \\ 48 & 2 & 63 & 19.5 & 37.5 & 9 & 13 & 5 & 52 \\ 52 & 2 & 62 & 48 & 37.5 & 9 & 13 & 5 & 44.5 \\ 55{,}5 & 2 & 60 & 28 & 37.5 & 9 & 13 & 5 & 48 \\ 41.5 & 15.5 & 57 & 21.5 & 52 & 26 & 31.5 & 29.5 & 44.5 \\ 41.5 & 15.5 & 58 & 33 & 52 & 26 & 31.5 & 29.5 & 34.5 \\ 41.5 & 24 & 59 & 21.5 & 52 & 7 & 11 & 17.5 & 37.5 \end{bmatrix} \tag{12}$$

Upon finishing the matrix, we count up all the values, i.e. the total amount of the lines according to *Formula 13*.

$$r_i = \sum_{j=1}^{k} r_{ij} \tag{13}$$

By ordering the values from the least to the highest, we got the final order of the alternatives based on r_i values:

- v_2 Volvo FE Electric ELECTRICITY;
- v_4 Lion 8 EL ELECTRICITY;
- v_7 Scania P 340 BIOGAS;
- v_3 Dennis Eagle EV ELECTRICITY;

— v_5 Renault Trucks D Wide CNG;
— v_6 IVECO Stralis CNG;
— v_1 Mercedes Benz GEN2H + Strummer HYDROGEN.

The ORESTE method consists of three additional steps for comparing the alternatives, where possible.

The fourth step includes calculating normalised preference intensities using tables for preferences between the alternatives, where + indicates that a_i is preferred over a_j (see *Table 6*). Upon compiling the tables for all criteria, we created the I_{ij} criteria set indicating the preferred criterion within I_{ij}. The resulting combination of the alternatives acquired 0 value, implying no comparability between the criteria.

Table 6 – ORESTE – Preferences between the alternatives of criterion k_1

f1	1	2	3	4	5	6	7
1	-	+	+	+	-	-	-
2	-	-	+	+	-	-	-
3	-	-	-	+	-	-	-
4	-	-	-	-	-	-	-
5	-	+	+	+	-	-	-
6	-	+	+	+	-	-	-
7	-	+	+	+	-	-	-

Source: the Authors

Based on processing the I_{ij} set, we could calculate the preference intensities using the following *Formula 14*:

$$c_{ij} = \sum_{h\in Iij}(r_{jh} - r_{ih}), i,j = 1,\dots,p, \tag{14}$$

where I_{ij} is the criteria set preferring a_i over a_j.

The preference intensity values are suggested in the following matrix (15):

$$C = \begin{bmatrix} 0 & 8.5 & 40 & 22.5 & 28.5 & 40 & 8 \\ 84 & 0 & 32.5 & 16 & 90 & 1015 & 51 \\ 91.5 & 8.5 & 0 & 7 & 88 & 88 & 49 \\ 89 & 7 & 22 & 0 & 88 & 93 & 49 \\ 34 & 20 & 42 & 27 & 0 & 12.5 & 21 \\ 43 & 29 & 39.5 & 29.5 & 10 & 0 & 12.5 \\ 61.5 & 29 & 51 & 36 & 58.5 & 63 & 0 \end{bmatrix} \tag{15}$$

Upon finishing the matrix, we calculated the maximum intensity according to *Formula 16*:

$$c^{max} = k^2(p - 1) \tag{16}$$

The resulting c^{max} allows us to determine the values of the normalised preference intensities according to *Formula 17*, and a follow-up recording in C^n.

$$c_{ij}^n = \frac{c_{ij}}{c^{max}} \tag{17}$$

Matrix C^n (*Formula 18*) is confined to four decimal numbers.

$$C^n = \begin{bmatrix} 0 & 0.0175 & 0.0823 & 0.0463 & 0.0586 & 0.0823 & 0.0165 \\ 0.1728 & 0 & 0.0669 & 0.0329 & 0.1852 & 0.2088 & 0.1049 \\ 0.1883 & 0.0175 & 0 & 0.0144 & 0.1811 & 0.1811 & 0.1008 \\ 0.1831 & 0.0144 & 0.0453 & 0 & 0.1811 & 0.1914 & 0.1008 \\ 0.0700 & 0.0412 & 0.0864 & 0.0556 & 0 & 0.0257 & 0.0432 \\ 0.0885 & 0.0597 & 0.0813 & 0.0607 & 0.0206 & 0 & 0.0257 \\ 0.1265 & 0.0597 & 0.1049 & 0.0741 & 0.1204 & 0.1296 & 0 \end{bmatrix} \tag{18}$$

Step 5 tests the state of indifference, which must fulfil two requirements to be considered indifferent. First, both normalised preference intensities must be lower than the selected α value (*Formula 19*). Second, the difference between both normalised preference intensities is not bigger than the selected value β (*Formula 20*).

$$c_{ij}^{n} \leq \alpha \tag{19}$$

$$c_{ij}^{n} - c_{ji}^{n} \leq \beta \tag{20}$$

Values α and β are subject to restrictions (*Formulae 21* and *22*), which must be adhered to.

$$\alpha \leq \frac{1}{2(p-1)} \tag{21}$$

$$\beta \leq \frac{1}{k(p-1)} \tag{22}$$

We determined the marginal values from the calculations above: $\alpha \leq 0{,}08$, $\beta \leq = 0{,}015$. The requirements always comply with zero values on the matrix diagonal, setting the indifferent values at $c_{11}, c_{22}, c_{33}, c_{44}, c_{55}, c_{66}, c_{77}$ and $c_{15}, c_{51}, c_{56}, c_{65}$. In this step, we can determine matrix elements that undergo an incomparability test, including all non-indifferent components: c_{21}, c_{23}, c_{24}, c_{25}, c_{26}, c_{27}, c_{31}, c_{35}, c_{36}, c_{41}, c_{43}, c_{45}, c_{46}, c_{47}, c_{61}, c_{71}, c_{73}, c_{75}.

The last step of the ORESTE method involves the incomparability test of the prescribed elements. Unless indifferent, the alternatives are incomparable if meeting requirements suggested in *Formula 23:*

$$\frac{c_{ji}^{n}}{c_{ij}^{n} - c_{ji}^{n}} \geq \gamma \tag{23}$$

Parameter γ involves a threshold value that should not be exceeded, as defined by *Formula 24*.

$$\gamma \geq \frac{k-2}{4} \tag{24}$$

If comparable, a_i is preferred over a_j, presuming that $c_{ij}^{n} \geq c_{ji}^{n}$. The final table helps us understand the placement of *I* and *N* symbols, > for line and < for column preferences.

Like the PROMETHEE, the ORESTE prioritises electric vehicles, indicating exactly the same car. *Table 7* suggests whether some alternatives are incomparable or indifferent and shows the preference.

Table 7 – ORESTE – Preference table of the alternatives

	v_1	v_2	v_3	v_4	v_5	v_6	v_7
v_1	I	<	<	<	I	N	<
v_2	>	I	>	>	>	>	>
v_3	>	<	I	<	>	>	N
v_4	>	<	>	I	>	>	N
v_5	I	<	<	<	I	I	<
v_6	N	<	<	<	I	I	<
v_7	>	<	N	N	>	>	I

Source: the Authors

5. DISCUSSION

Table 8 suggests similar results of both methods, prioritising electric vehicles. According to the criteria rating scale, both techniques preferred Volvo FE Electric. Despite the global promotion of hydrogen vehicles, the car ranked fifth in the PROMETHEE and the last in the ORESTE method. CNG vehicles occupied the sixth and seventh place (i.e. fifth and sixth position). Despite the heavy usage of these trucks in České Budějovice, they might not be the best option, compelling the city to consider other alternatives for waste collection.

Table 8 – Comparing the results of the PROMETHEE and the ORESTE method

Rank	PROMETHEE	ORESTE
1.	Volvo FE Electric ELECTRICITY	Volvo FE Electric ELECTRICITY
2.	Lion 8 EL ELECTRICITY	Lion 8 EL ELECTRICITY
3.	Dennis Eagle EV ELECTRICITY	Scania P 340 BIOGAS
4.	Scania P 340 BIOGAS	Dennis Eagle EV ELECTRICITY
5.	Mercedes Benz GEN2H + HYDROGEN	Renault Trucks D Wide CNG
6.	Renault Trucks D Wide CNG	IVECO Stralis CNG
7.	IVECO Stralis CNG	Mercedes Benz GEN2H HYDROGEN

Source: the Authors

Our results observe the assessed criterion preference. If the criteria rating scale were different, the vehicle ranking would have changed, as the scale was defined by the experts. The final ranking of electric vehicles was influenced by the high criterion preference of city gas stations, fuel potential within the next ten years and the eco-friendliness of the fuel, assigning a high rating to the electric cars [25]. On the other hand, experts did not give much importance to criteria like maximum mileage or refuelling time, where electric propulsions did not excel at all [26]. Hydrogen alternatives raise a disputable issue [27] as they have enormous potential but fail in the number of city gas stations and consume a lot of fossil fuels for production. CNG vehicles also face an uncertain future [28], heavily relying on fossil fuels.

6. CONCLUSION

The study deals with urban logistics in the city of České Budějovice. It aims to suggest logistic solutions in order to improve the traffic situation and mitigate environmental impacts, with a special emphasis on waste collection vehicles. The authors use multicriteria decision making methods to compare various types of propulsion/fuel.

Specifically, we focused on the options that assume ecological responsibility and maintain environmental sustainability, selecting the best option for city waste collection. Some of these vehicles already use CNG, which is more eco-unfriendly than biogas, electricity and hydrogen, and its future use is uncertain. We compared CNG-fuelled vehicles with more eco-friendly unconventional propulsions for waste collection.

We chose two combinations of multicriteria decision-making, including the Saaty pairwise comparison method, the PROMETHEE, the Fuller method and the ORESTE. These techniques yielded very similar results, with Volvo FE Electric as the best scenario. Overall, vehicles propelled by electricity ranked the highest. In one case, CNG trucks occupied the last place, facing a very uncertain future involving 100% fossil fuel. Our results include criteria weights assigned by experts. In the event of varying preferences, certainly, the results would be different.

When elaborating the study, the authors came to recommendations for further research in a subject discussed:

— It is necessary to examine the long-term environmental and economic impacts of applying alternative types of propulsions and fuels for performing logistic activities in city logistics.
— An important aspect is also to examine the potential for reducing greenhouse gas emissions and other harmful substances when using alternative types of fuel.
— To conduct wider comparative research of city logistics approaches in other cities and regions. Expanding the research to other cities with different logistic and environmental conditions would allow for the verification of the transferability of the outcomes and recommendations to other urban areas with varying requirements for city logistics.
— Last but not least, it is necessary to continuously analyse technological development trends and innovative approaches in the field of electromobility and hydrogen technologies that could affect city logistics measures.
— To examine the possibilities of implementing intelligent transport and traffic systems to optimise city logistics and minimise traffic overload.

At the same time, multiple other possibilities for future research steps in the addressed subject matter open up:

- Deepening the analysis of infrastructure costs: It is imperative to focus on the analysis of costs associated with construction, development and maintenance of the relevant infrastructure for various alternative propulsion systems, above all, charging and refuelling stations for electric and hydrogen vehicles, CNG- or biogas-propelled vehicles, wherein these costs are often higher compared to conventional technologies.
- Long-term monitoring of operational costs: It would be reasonable to conduct further studies that observe the long-term operational costs and sustainability of selected technologies in practice, which would allow for the validation of this study findings and updating of criteria based on real operational data.

This research was limited geographically to the city of České Budějovice and focused on the specific segment of city logistics, namely waste collection. Another restriction lies in uncertainty regarding the long-term availability and ecological question (i.e. eco-friendliness) of the CNG fuel, electric and hydrogen propulsions. The research focused only on the limited number of specific types of propulsion/fuel, which narrows the possibilities of conducting sufficiently comprehensive comparison and analysis of ecological alternatives with a limited explanatory value.

Furthermore, some criteria and input data for the selection of vehicles were limited to expert assessments and available data, which could affect the accuracy of the assessment of individual criteria and the subsequent determination of compromise variants.

ACKNOWLEDGEMENTS

The paper was supported by the VEGA Agency, Grant No. 1/0340/24 "Research on alternatives to decarbonisation in rail transport from the point of view of social costs", at Faculty of Operations and Economics of Transport and Communication, University of Žilina, Slovakia.

REFERENCES

[1] Cattaruzza D, et al. Vehicle routing problems for city logistics. *EURO Journal on Transportation and Logistics*. 2017;6(1):51-79. DOI: 10.1007/s13676-014-0074-0.

[2] Gonzalez-Feliu J. *Models and methods for the city logistics: The two-echelon capacitated vehicle routing problem*. PhD thesis. Politecnico di Torino, Italy; 2008.

[3] Taniguchi E, van der Heijden RECM. An evaluation methodology for city logistics. *Transport Reviews*. 2010;20(1):65-90. DOI: 10.1080/014416400295347.

[4] Crainic TG, Ricciardi N, Storchi G. Models for evaluating and planning city logistics systems. *Transportation Science*. 2009;43(4):407-548. DOI: 10.1287/trsc.1090.0279.

[5] Fedorko G, et al. Application of simulation model in terms of city logistics. Proceedings of the *20th International Scientific on Conference Transport Means 2016, 5-7 Oct. 2016, Juodkrante, Lituania*. 2016. p. 169-174.

[6] Ruesch M, et al. Sustainable goods supply and transport in conurbations: Freight strategies and guidelines. *Procedia - Social and Behavioral Sciences*. 2012;39:116-133. DOI: 10.1016/j.sbspro.2012.03.095.

[7] Sommerauerová D, Chocholáč J, Urbanová K. Sustainable green city logistics solution for the Prague agglomeration and retail chain. *Perner's Contact*. 2020;15(2). DOI: 10.46585/pc.2020.2.1644.

[8] Petro F, Konečný V. Calculation of external costs from production of direct and indirect emissions from traffic operation. *Transportation Research Procedia*. 2019;40:1162-1167. DOI: 10.1016/j.trpro.2019.07.162.

[9] Allen J, et al. The role of urban consolidation centres in sustainable freight transport. *Transport Reviews*. 2012;32(4):473-490. DOI: 10.1080/01441647.2012.688074.

[10] Browne M, et al. *Urban freight consolidation centres: Final report. Transport Studies Group*. University of Westminster, UK; 2005. https://ukerc.rl.ac.uk/pdf/RR3_Urban_Freight_Consolidation_Centre_Report.pdf [Accessed 25 July 2021].

[11] Song L, et al. Environmental benefits of using new last-mile solutions and using electric vehicles in China. *Transportation Research Record*. 2023;2678(1):473-489. DOI: 10.1177/03611981231171149.

[12] Duangekanong S. Determining behavioral intention of logistic and distribution firms to use electric vehicles in Thailand. *Journal of Distribution Science*. 2023;21(5):31-41. DOI: 10.15722/jds.21.05.202305.31.

[13] Sierpiński G, et al. Challenges related to the implementation and development of electromobility in cities. *Springer Proceedings in Business and Economics. TranSopot Conference 2019, 27-29 May 2019, Sopot.* 2021. p. 203-213. DOI: 10.1007/978-3-030-50010-8_18.

[14] Van Duin JHR, Quak H, Muñuzuri J. New challenges for urban consolidation centres: A case study in The Hague. *Procedia - Social and Behavioral Sciences*. 2010;2(3):6177-6188. DOI: 10.1016/j.sbspro.2010.04.029.

[15] Lindholm M, Behrends S. Challenges in urban freight transport planning – A review in the Baltic Sea Region. *Journal of Transport Geography*. 2012;22:129-136. DOI: 10.1016/j.jtrangeo.2012.01.001.

[16] Fu J, Jenelius E. Transport efficiency of off-peak urban goods deliveries: A Stockholm pilot study. *Case Studies on Transport Policy*. 2018;6(1):156-166. DOI: 10.1016/j.cstp.2018.01.001.

[17] Justiani S, Wibowo B. The economic and environmental benefits of collaborative pick-up in urban delivery systems. *LOGI – Scientific Journal on Transport and Logistics*. 2022;13(1):245-256. DOI: 10.2478/logi-2022-0022.

[18] Lasota M, et al. Method for delivery planning in urban areas with environmental aspects. *Sustainability*. 2024;16:1571. DOI: https://doi.org/10.3390/su16041571.

[19] Baric D, Zeljko L. Multi-criteria decision-making on road transport vehicles by the AHP method. *The Archives of Automotive Engineering – Archiwum Motoryzacji*. 2021;94(4):17-26. DOI: 10.14669/AM.VOL94.ART2.

[20] Samson-Bręk IA, Matuszewska A. Possibilities of reducing greenhouse gas emissions in agriculture on the example of a biogas plant. *The Archives of Automotive Engineering – Archiwum Motoryzacji*. 2019;86(4):127-142. DOI: 10.14669/AM.VOL86.ART9.

[21] Gorzelanczyk, P. Analysis of the logistics process of waste transport in the city of Pila (The case study from Poland). *LOGI – Scientific Journal on Transport and Logistics*. 2021;12(1):46-57. DOI: 10.2478/logi-2021-0005.

[22] Saaty TL. *Decision making for leaders: The analytic hierarchy process for decisions in a complex world*. RWS Publications. Pittsburgh, Pennsylvania, USA; 1990.

[23] Saaty TL. Decision making with the analytic hierarchy process. *International Journal of Services Sciences*. 2008;1(1):83-98. DOI: 10.1504/IJSSci.2008.0175.

[24] Saaty TL, Vargas LG, Wendell RE. Assessing attribute weights by rations. *Omega – International Journal of Management Science*. 1983;2(1):9-13.

[25] Tucki K, et al. The Impact of Fuel Type on the Output Parameters of a New Biofuel Burner. *Energies.* 2019;12,1383. DOI: 10.3390/en12071383.

[26] Paisarnvirosrak N, Rungrueang P. Firefly algorithm with tabu search to solve the vehicle routing problem with minimized fuel emissions: Case study of canned fruits transport. *LOGI – Scientific Journal on Transport and Logistics*. 2023;14(1):263-274. DOI: 10.2478/logi-2023-0024.

[27] Hren R, et al. Hydrogen production, storage and transport for renewable energy and chemicals: An environmental footprint assessment. *Renewable and Sustainable Energy Reviews*. 2023;173,113113. DOI: 10.1016/j.rser.2022.113113.

[28] Fattah MdA, et al. Environmental and economic benefits of CNG conversion on three-wheelers in a developing city, Khulna, Bangladesh. *Transportation Engineering*. 2023;13,100199. DOI: 10.1016/j.treng.2023.100199.

Ondrej Stopka, Vladimír Ľupták, Mária Stopková, Branislav Šarkan, Jaroslav Mašek

Metodika výběru ekologicky nejpřijatelnějšího vozidla pro svoz odpadu

Abstrakt

Svoz odpadu v městských aglomeracích, jako součást city logistických přístupů a řešení, se stal jedním z klíčových témat ve vztahu k stále náročnějších požadavkům na logistické operace ve městech zatížených vysokými dopravními objemy, což zhoršuje kvalitu života a životní prostředí ve městech. Dopravní kongesce trápí město České Budějovice zejména během dopravních špiček. Tyto zácpy by měly být částečně eliminovány plánovanou výstavbou nových silnic, které odvedou tranzitní dopravu z centra města. I přes tato nápravná opatření si současná dopravní a logistická situace vyžaduje další kroky ke zlepšení. Článek se zaměřuje na svoz odpadu, který významně ovlivňuje veškeré dopravní toky v Českých Budějovicích. V současnosti město nasazuje také finančně nákladné svozní automobily poháněné CNG, které vypouštějí mnoho škodlivých emisí. Cílem článku je zvážit a vyhodnotit nové přístupy ve vztahu k svozu odpadu, které by mohly fungovat v souladu s ekologickými principy a udržitelným rozvojem měst. Tato otázka zahrnuje vozidla pro svoz odpadu poháněná vodíkem, elektřinou, bioplynem a CNG. Jinými slovy je třeba rozhodnout, zda má smysl investovat do moderních a udržitelných technologií pohonu vozidel pro svoz odpadu v dané aglomeraci. K tomu účelu jsou aplikovány metody vícekriteriálního rozhodování, konkrétně Saatyho metoda a Fullerova metoda pro kvantifikaci vah kritérií a metody PROMETHEE a ORESTE ke stanovení kompromisního (ideálního) řešení. Výsledky zahrnují rozhodovací proces a návrh metodiky pro určení pořadí posuzovaných vozidel pro svoz odpadu na základě relevantních kritérií stanovených expertním hodnocením.

Klíčová slova

city logistika; svoz odpadu; vícekriteriální rozhodování; alternativní zdroje energie.